

The nature of the HE0450-2958 system

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ABSTRACT

Magain et al. (2005) argued that the host galaxy of the quasar in HE0450-2958 is substantially under-luminous given the likely mass of its nuclear black hole. Using kinematical information from the spectra of the quasar and the companion galaxy, an ultra-luminous infrared galaxy, we test the hypothesis that the black hole powering the quasar was ejected from the companion galaxy during a merger. We find that the ejection model can be securely ruled out, since the kick velocity required to remove the black hole from the galaxy is $\gtrsim 500$ km/s, inconsistent with the presence of narrow emission line gas at the same redshift as the quasar nucleus. We also show that the quasar in HE0450-2958 has the spectral characteristics of a narrow-line Seyfert 1 galaxy and calculate a mass for its black hole that is roughly an order of magnitude smaller than estimated by Magain et al. The predicted luminosity of the host galaxy is then consistent with the upper limits inferred by those authors.

1 INTRODUCTION

HE0450-2958 is a bright quasar at redshift $z = 0.285$. HST images revealed that the system is double, with an ultra-luminous infrared galaxy (ULIRG) situated ~ 1.5 arc-sec from the quasar (Boyce et al 1996; Canalizo & Stockton 2001). Recently, Magain et al. (2005) reported that the host galaxy of the quasar is substantially under-luminous, based on the quasar’s luminosity and on a likely value for M_{\bullet} , the mass of its nuclear supermassive black hole (SBH). Magain et al. proposed either that the quasar host galaxy is dark, or that an otherwise “naked” SBH had acquired gas while moving through intergalactic space.

Here we examine these hypotheses in light of additional evidence from the spectra of the quasar and the companion galaxy. The quasar spectrum reveals it to be a typical narrow-line Seyfert 1 galaxy (Osterbrock & Pogge 1985), not a giant elliptical galaxy as assumed by Magain et al. (2005). We infer a much smaller luminosity for the host galaxy, consistent with the upper limits derived by those authors. We also critically examine the most natural model for a “naked” SBH, namely, a SBH that was ejected from the companion galaxy during the merger that created the ULIRG (Merritt et al. 2004). We show that the ejection model can be securely ruled out, since the quasar spectrum indicates the presence of narrow emission line gas extending out to a distance of ~ 1 kpc from the nucleus that is moving at the same velocity as the broad-line gas. The narrow-line gas could not have remained bound to the SBH if it were ejected from the companion galaxy.

2 SPECTRAL ANALYSIS

HE0450-2958 was observed during November 27 2001 using the UV Focal Reducer and low-dispersion spectrograph (FORSl) on Unit Telescope 1 of the VLT (PI: M. Courbin). The instrument was operated in MOS mode with a long-slit position angle of $\sim 55^\circ$. This allowed the contributions from the ULIRG, quasar and the nearby G-type star to be gathered simultaneously in slit no. 9. In total, five spectra were obtained of HE0450-2958: three of 1200 s duration using the 600B grism centered at 4620Å, and two of 1800 s duration using the 600R (6270Å) and 600I (7940Å) grisms. These data, including all relevant calibration files, were retrieved from the VLT data archive ¹.

The data were reduced using standard IRAF² routines. Bias and flat-field subtraction were carried out before wavelength calibration with HeArNe arcs. Cosmic ray subtraction was facilitated with a median combine, in the case of the three 600B exposures, and with a median filter and rigorous visual inspection in the 600R and 600I cases. Background subtraction was performed by removing a third-order polynomial fitted to the sky components in the spatial direction. Flux calibration was carried out by fitting a 5700K (G-type) black body spectrum to the observed star, and scaling to the fluxes observed through the High Resolution Channel of

¹ <http://archive.eso.org/>

² IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

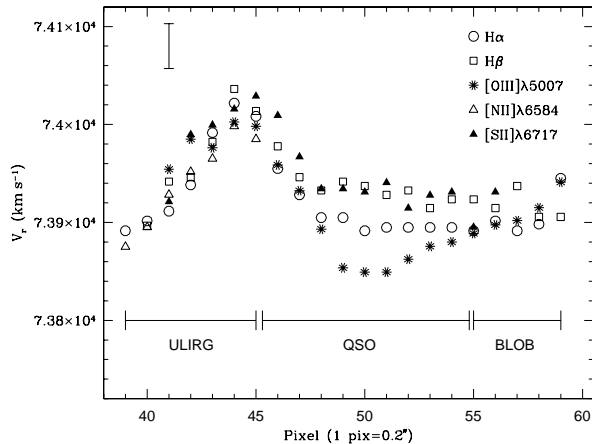


Figure 1. Radial velocities obtained from the peak wavelengths of the strongest emission lines along the slit. The locations of the galaxy, quasar and “blob” identified by Magain et al. (2005) are indicated.

the Advanced Camera for Surveys aboard the *Hubble Space Telescope* (no. 10238, PI: Courbin).

Figure 1 shows the velocities derived from the peak wavelengths of the strongest emission lines along the slit; the regions dominated by the ULIRG, the quasar and the Magain et al. (2005) “blob” are indicated. In the region dominated by the galaxy, the velocities show the pattern of a rotation curve, with peak-to-peak such a amplitude of ~ 140 km s^{-1} . This value seems small for such a luminous galaxy, but the HST image suggests that the orientation of the slit, aligned to include the star, quasar and ULIRG, is far from the major axis of the galaxy. According to the rotation curve, the systemic velocity of the galaxy is 73950 ± 20 km s^{-1} . In the region dominated by the quasar, the velocities obtained from the $\text{H}\alpha$, $\text{H}\beta$, $[\text{NII}]\lambda 6584$ and $[\text{SII}]\lambda 6717$ emission lines do not vary within the uncertainties, and the average value is 73920 ± 20 km s^{-1} , indicating a blueshift relative to the systemic velocity of the galaxy of only 30 km s^{-1} , consistent within the errors with zero. The $[\text{OIII}]\lambda 5007$ emission line is blue-shifted relative to the other emission lines by approximately 60 km s^{-1} . However such a blueshift in $[\text{OIII}]\lambda 5007$ is often observed in AGN (Nelson & Whittle 1995; Bian et al. 2005; Boroson 2005). In the region dominated by the emission of the blob, this blueshift is not observed, and the velocities derived from the $[\text{OIII}]\lambda 5007$ emission line are the same as those obtained from the other lines. In summary, our measurements show similar systemic velocities for the ULIRG, quasar and blob.

The blue spectrum of the galaxy (Figure 2) shows a number of absorption-line features, in particular, high-order Balmer lines indicative of an intermediate-age ($\sim 10^8$ yr) stellar population. In order to better quantify the age of the stellar population and to obtain an estimate for the stellar velocity dispersion, we performed a spectral synthesis using

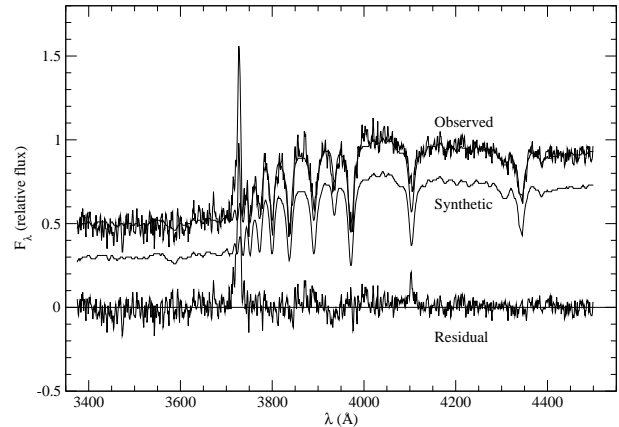


Figure 2. The blue spectrum of the ULIRG, together with the synthetic spectrum and the residual between the two. The synthetic spectrum is plotted twice: superimposed on the galaxy spectrum and shifted vertically for clarity.

the code STARLIGHT of Cid Fernandes et al. (2005). This code uses a basis of stellar population templates, each one corresponding to a given metallicity and age, to synthesize the galaxy spectrum, and it gives as output the contribution of each template to the total light at $\lambda 4020\text{\AA}$; the internal reddening; and the velocity dispersion. The contribution of the quasar, which contaminates both the continuum and the emission lines of the galaxy spectrum, has also been included in the synthesis. The results of the synthesis (Figure 2) yield the following contributions to the light of the ULIRG at $\lambda 4020$: $\sim 25\%$ from the quasar continuum, $\sim 50\%$ from stars with ages around 10^8 yr and $\sim 25\%$ from older stars. The total stellar mass is $\sim 6 \times 10^{10} M_{\odot}$, with the major uncertainty due to the quasar continuum contribution. The internal reddening is $A_V = 0.4$ mag and the velocity dispersion is $\sigma = 190 \pm 25$ km s^{-1} . The synthesis strongly points to a major burst of star formation $\sim 10^8$ yr ago.

3 EJECTION HYPOTHESIS

The low luminosity of the quasar host, coupled with its proximity to a ULIRG, leads naturally to the hypothesis that the SBH powering the quasar was ejected from the ULIRG following a merger. Two ejection mechanisms have been discussed: gravitational radiation recoil during the coalescence of a binary SBH (Favata et al. 2004); or a gravitational slingshot involving three SBHs, if the merger happened to bring a third SBH into the center of a galaxy containing an uncoalesced binary (Mikkola & Valtonen 1990).

The quasar is displaced 1.5 arcsec from the center of the ULIRG, corresponding to a projected separation of ~ 6.5 kpc. This is much greater than the galaxy’s half-light radius implying an ejection velocity V_{kick} comparable to the central escape velocity from the galaxy V_{esc} . The distribution of mass around the companion galaxy of HE0450-2958 is unknown. However, Tacconi et al. (2002) find that the light distributions in a sample of 18 ULIRGs are reasonably well fit by de Vaucouleurs profiles with effective (projected half-light) radii of $R_e \approx 1$ kpc, similar to those of luminous E galaxies. They derive kinematical masses of $0.3 \times 10^{11} M_{\odot} \lesssim M \lesssim 5 \times 10^{11} M_{\odot}$, consistent with

Table 1. Mass Models

	galaxy				halo		both
	M ($10^{11} M_{\odot}$)	R_e (kpc)	V_{esc} (km s^{-1})	M ($10^{12} M_{\odot}$)	$r_{1/2}$ (kpc)	V_{esc} (km s^{-1})	V_{esc} (km s^{-1})
Model 1	0.15	1.10	440	2.0	200	500	664
Model 2	1.50	1.43	1520	2.0	200	500	1597

the estimate presented above from population synthesis of $0.5 - 0.8 \times 10^{11} M_{\odot}$. The mean stellar velocity dispersion in their sample is 180 km s^{-1} , consistent with the population synthesis estimates presented above. We accordingly modelled the baryonic mass distribution around the ULIRG as if it were a normal, spherical E galaxy of mass M_{gal} , and used the empirical correlations between E-galaxy mass, luminosity, effective radius and Sersic index (Magorrian et al. 1998; Graham & Guzmán 2003; Ferrarese et al. 2005) to derive its gravitational potential.

Table 1 gives the parameters of two mass models for the companion galaxy. Model 1 has a baryonic mass of $1.5 \times 10^{10} M_{\odot}$, roughly the mass of a $M_B \approx -18$ dE galaxy and a factor of \sim two *smaller* than the smallest ULIRG mass inferred by Tacconi et al. Model 2 has $M_{gal} = 1.5 \times 10^{11} M_{\odot}$, the stellar mass of a $M_B \approx -20$ E galaxy, and close to the average mass of the galaxies in the Tacconi et al. sample. We also included a dark-matter halo; because the contribution of dark matter to the gravitational force on scales $\lesssim 10$ kpc is probably much less than that of the baryons, we considered only a single halo model. As templates for the dark matter, we considered the four “galaxy-sized” halos in the Diemand et al. (2004) Λ CDM simulations, which have virial masses in the range $1.0 \times 10^{12} M_{\odot} \leq M_{DM} \leq 2.2 \times 10^{12} M_{\odot}$. Fits to $\rho(r)$ for these halos are given in Graham et al. (2005); based on these fits, central escape velocities lie in the range $480 \text{ km s}^{-1} \leq V_{esc} \leq 600 \text{ km s}^{-1}$, and the ΔV in climbing to 10 kpc is $210 \text{ km s}^{-1} \leq \Delta V \leq 310 \text{ km s}^{-1}$. Our adopted halo model (Table 1) had a mass of $2.0 \times 10^{12} M_{\odot}$ (virial mass $1.1 \times 10^{12} M_{\odot}$), half-mass radius 200 kpc and central escape velocity $\sim 500 \text{ km s}^{-1}$, similar to model G1 in Diemand et al. (2004). By comparison, the virial mass of the Milky Way halo is believed to be $1 - 2 \times 10^{12} M_{\odot}$ (Klypin et al. 2002).

In de Vacouleurs-like mass models, the ΔV in climbing from the very center out to a distance of a few parsecs can be considerable due to the high nuclear density (e.g. Young (1976)). The mass distribution of the companion galaxy following the merger is unknown on these small radial scales, and in any case, the SBH would carry with it the mass of the inner few parsecs, modifying the potential. Accordingly, we placed the SBH initially at a distance of 10 pc from the galaxy center when computing post-ejection trajectories.

Figure 3 shows the results. As expected, kicks of $\sim 500 \text{ km s}^{-1}$ (Model 1) and $\sim 1500 \text{ km s}^{-1}$ (Model 2) are required in order for the SBH to climb a distance of 10 kpc from the center of the galaxy. *This result essentially rules out radiation recoil as the origin of the kick*, since the maximum amplitude of the recoil is believed to be less than 500 km s^{-1} (Merritt et al. 2004) and probably no more than 250 km s^{-1} (Blanchet et al. 2005). Three-body recoils might still

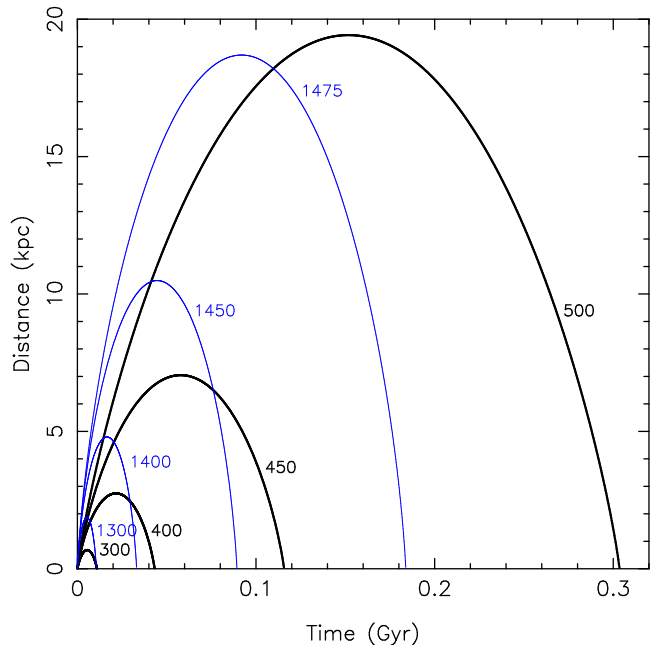


Figure 3. Trajectory of a kicked SBH in two models for the mass distribution of the companion galaxy (Table 1). *Black (thick) curves:* Model 1; *blue (thin) curves:* Model 2. Curves are labelled by V_{kick} in km s^{-1} .

work, however the largest ΔV in a three-body interaction is experienced by the *smallest* body. But Figure 3 constrains *any* ejection model in a number of other ways:

1. A large V_{kick} implies a large velocity, $V \gtrsim 300 \text{ km s}^{-1}$, as the SBH moves past its current position. This is hard to reconcile with the essentially zero radial velocity difference between quasar and galaxy, unless the ejection velocity is fine-tuned or nearly perpendicular to the line of sight.

2. The time for the kicked SBH to reach a distance of 10 kpc is much shorter than 10^8 yr, again unless the gravitational potential and kick velocity are finely tuned. But the starburst occurred $\sim 10^8$ yr ago; thus, either the true separation of the SBH from the ULIRG is much greater than 10 kpc, or the ejection was delayed until a time of $\sim 10^8$ yr after the starburst.

3. A large V_{kick} implies that the ejected SBH will carry very little mass with it as it departs the galaxy. Material orbiting the SBH with velocity $v \gg V_{kick}$ before the kick will experience the kick as an adiabatic perturbation and will “instantaneously” acquire the specific momentum of the SBH. This argument suggests that the SBH will carry with it the mass contained initially within a region whose size

is less than r_{eff} , the radius at which the orbital velocity around the SBH is equal to V_{kick} , or

$$r_{eff} = \frac{GM_{\bullet}}{\sigma^2} \left(\frac{V_{kick}}{\sigma} \right)^{-2} \approx 10 M_8 \sigma_{200}^{-2} \left(\frac{V_{kick}}{\sigma} \right)^{-2} \text{ pc} \quad (1)$$

with $M_8 \equiv M_{\bullet}/10^8 M_{\odot}$ and $\sigma_{200} \equiv \sigma/200 \text{ km s}^{-1}$. Since $M_8 \approx 1$ (see below) and $V_{kick} \gtrsim 3\sigma$ (Figure 3), the entrained region will be of order 1 pc or less in size. This is probably sufficient to include the broad-line region (BLR) gas, which is expected to have a size ~ 0.3 pc based on the empirical scaling relation between BLR size and 5007Å luminosity (Kaspi et al. 2005; Greene & Ho 2005), but not larger structures.

4 SIZE OF THE NARROW-LINE REGION

The radius of the narrow-line region can be estimated from the ionization parameter and density of the emitting gas and the ionizing luminosity of the QSO. For an ionizing photon luminosity, Q , the ionization parameter in gas of density n at a distance r from the source can be defined as $U = Q/(4\pi R_{NLR}^2 n c)$. We estimate the ionizing photon luminosity by extrapolating the slope of the far UV ($\sim 600 - 1200\text{\AA}$) continuum as determined by Scott et al. (2004) from *FUSE* observations. After corrections for interstellar extinction and absorption, Scott et al.'s power-law ($f_{\nu} \propto \nu^{-\alpha}$) fit yields a spectral index $\alpha = -1.2 \pm 0.1$ and a flux at 1000\AA of $5.25 \times 10^{-27} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$. HE0450-2958 has a steep soft X-ray continuum, with a photon index $\Gamma = 3.1$ in the 0.1-2 keV ROSAT band (Brinkmann et al. 1997). Therefore, we extrapolate the UV power-law to a high energy cut-off of 0.1 keV. Adopting a luminosity distance of 1458 Mpc (assuming $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a matter density parameter $\Omega_m = 0.27$) the integration yields $Q \approx 1.2 \times 10^{56} \text{ photons s}^{-1}$.

The gas density was obtained from the relative intensities of the [SII] $\lambda\lambda 6717, 6731$ doublet. Although partially blended in the spectrum, Gaussian fits to the lines are well constrained and yield a ratio $I_{6717}/I_{6731} = 1.01 \pm 0.05$. This corresponds to a density $n \approx 1000 \text{ cm}^{-3}$.

We determined the ionization parameter from the ratio of the [OII] $\lambda 3727$ and [OIII] $\lambda 5007$ lines (Baldwin et al. 1981). The intensity ratio measured from the spectrum is $I_{3727}/I_{5007} = 0.13 \pm 0.05$. Using the empirical relation between this ratio and the ionization parameter given by Penston et al. (1990), we obtain $U \approx 0.014$. This value is broadly consistent with the more recent photoionization models presented by Groves et al. (2004).

Combining estimates for Q , n and U , we arrive at a radius $R_{NLR} \approx 1.5 \text{ kpc}$. This of course represents an ill-defined spatial average, since we have used integrated fluxes of emission lines representing different ionization states. Moreover, the determination of U is model-dependent and extrapolating the far UV power-law is, at best, a crude representation of the EUV continuum.³ Based on these considerations, R_{NLR} may be uncertain by a factor ~ 2 . It is, nevertheless, unsurprising that the NLR in a relatively luminous quasar

extends to a few kpc. Direct imaging of bright, low-redshift quasars in [OIII] with HST reveals NLR sizes ranging from 1.5 kpc to 10 kpc (Bennert et al. 2002). Indeed, the [OIII] luminosity of HE0450-2958 ($L_{[\text{OIII}]} \approx 3.6 \times 10^{43} \text{ erg s}^{-1}$) makes it comparable with the most luminous object in Bennert et al.'s sample, for which they determine an NLR radius of 10.5 kpc.

Such a large size for the NLR rules out the possibility that the NLR gas would remain bound to the SBH after ejection from the ULIRG (cf. equation 1). Post-ejection accretion of the NLR gas from a cloud is also unlikely, since the radius of the Bondi accretion column, r_{acc} , is given by an equation similar to eq. 1, after replacing V_{kick} by the relative velocity between SBH and gas cloud, implying $r_{acc} \ll 1 \text{ kpc}$ unless the ejected SBH has fortuitously matched velocities with the cloud.

5 MASS OF THE BLACK HOLE AND IMPLICATIONS FOR THE HOST GALAXY LUMINOSITY

As shown in Figure 4, *HE0450-2958 exhibits characteristics which unambiguously identify it as a narrow-line Seyfert 1* (NLS1; Grupe (2004)). Specifically, its broad Balmer lines have FWHM's $\approx 1300 \text{ km s}^{-1}$ (the conventional definition requires $\text{FWHM} < 2000 \text{ km s}^{-1}$; Osterbrock & Pogge (1985)), it has strong optical FeII emission features and, as already noted, it has a steep soft X-ray photon continuum. The currently-favored picture of NLS1's is that they represent an extreme AGN population characterized by relatively low-mass SBHs but high accretion rates (Peterson et al. 2000; Boroson 2002) — possibly substantially super-Eddington (Boller 2005). It follows that estimating M_{\bullet} from the quasar luminosity assuming a sub-Eddington accretion rate, as was done by Magain et al. (2005), is likely to be misleading. Here we adopt what we consider to be a more robust approach, and estimate a virial mass based on the velocity dispersion (v) and radius (R_{BLR}) of the broad-line region: $M_{BH} \sim v^2 R_{BLR}/G$ (Wandel et al. 1999; Kaspi et al. 2000; Vestergaard 2002).

In this method, the BLR velocity dispersion is derived from the broad-line widths while the BLR radius is inferred from the radius-luminosity relation derived from reverberation mapping (Kaspi et al. 2000; Peterson et al. 2004). Here, we use the recent revision of Kaspi et al. (2000)'s virial formula presented by Greene & Ho (2005). This requires measurements of the $H\beta$ FWHM ($v = \sqrt{(3)/2} \times \text{FWHM}$) and the continuum luminosity at 5100\AA (λL_{5100}). Our measurements of these quantities yield $\text{FWHM}(H\beta) \approx 1270 \text{ km s}^{-1}$ and $\lambda L_{5100} \approx 4.6 \times 10^{45} \text{ erg s}^{-1}$, respectively. Inserting these values into equation (5) of Greene & Ho, we obtain $M_{BH} = (9 \pm 1) \times 10^7 M_{\odot}$. Greene & Ho's alternative virial formula, which employs the luminosity and FWHM of the broad $H\alpha$ line yields a consistent result, albeit with greater uncertainty: $M_{BH} = (6_{-3}^{+5}) \times 10^7 M_{\odot}$. These masses are subject to a systematic uncertainty of a factor ~ 3 related to the poorly-known structure, kinematics and aspect of the BLR (e.g., Onken et al. (2004)). Nevertheless, at face value, the virial method yields a SBH mass that is an *order of magnitude* less than the value $M_{\bullet} \approx 8 \times 10^8 M_{\odot}$ adopted by Magain et al. (2005).

³ However, the $H\alpha$ photon luminosity is $\approx 10^{56} \text{ photons s}^{-1}$ which, assuming photoionization, implies that our value for Q is underestimated by at least a factor ~ 3 .

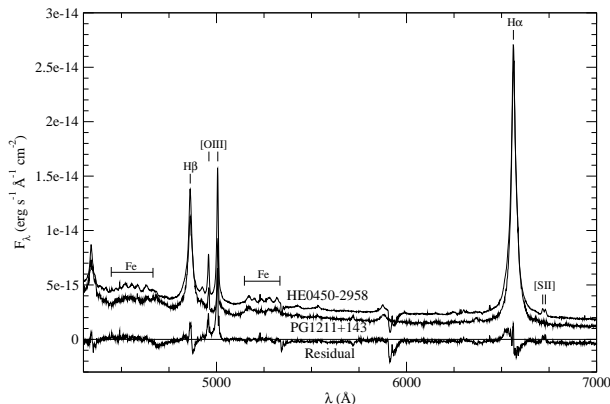


Figure 4. Comparing the quasar spectrum with that of PG1211+143, a radio-quiet quasar with steep X -ray spectral index that is classified spectroscopically as a NLS1 (Constantin & Shields 2003). HE0450-2958 is plotted in absolute flux units, PG1211+143 in absolute units minus $10^{-15} \text{ erg s}^{-1} \text{ \AA}^{-1} \text{ cm}^{-2}$. Residuals are plotted along the bottom with a solid straight line highlighting zero.

The host galaxies of NLS1s are spirals, often barred (Crenshaw et al. 2003), but relatively little is known about their systematic properties. The tight correlation between bulge velocity dispersion and SBH mass that characterizes quiescent elliptical galaxies and bulges (Ferrarese & Merritt 2000) also appears to be valid for the bulges of active galaxies, including NLS1s (Ferrarese et al. 2001; Botte et al. 2005). Adopting $M_{\bullet} = 9 \times 10^7 M_{\odot}$, we infer a bulge velocity dispersion $\sigma \approx 180 \text{ km s}^{-1}$. Near-IR bulge luminosities also correlate tightly with M_{\bullet} (Marconi & Hunt 2003); we infer a K -band absolute magnitude for the stars in the bulge of $M_K \approx -23.4$. Visual bulge magnitudes are more poorly correlated with M_{\bullet} . Adopting the Ferrarese & Ford (2005) relation gives an absolute blue magnitude $M_B = -18.9 \pm 0.5$; alternately, applying a $B - K$ color correction of 4.0 to M_K (Peletier & Balcells 1996) gives $M_B \approx -19.4$. Computing M_B directly from σ via the Faber-Jackson (1976) relation gives a similar value. Even more uncertain is the predicted total (bulge+disk) luminosity. Assuming an Sa host (Whittle 1992) implies a disk-to-bulge ratio of ~ 1.5 (Simien & de Vaucouleurs 1986) and a total visual magnitude $M_V \approx -21$. While very uncertain, this estimate is 2.0–2.5 magnitudes fainter than Magain et al. (2005)’s estimate ($-23.5 \leq M_V \leq -23.0$) based on a $\sim 10\times$ larger assumed value of M_{\bullet} , and consistent with their conclusion that the host galaxy must be at least 4–5 magnitudes fainter than the quasar ($M_V = -25.8$).

6 CONCLUSIONS

The HE0450-2958 system consists of a ULIRG that experienced a major starburst $\sim 10^8$ yr ago, situated at ~ 7 kpc projected separation from a quasar having the spectral characteristics of a narrow-line Seyfert 1. The quasar host, presumably an early-type spiral galaxy, is expected to have a bulge luminosity $M_K \approx -23.4$ ($M_V \approx -21$). Upper limits on the luminosity of the quasar host (Magain et al. 2005) are consistent with the expected total luminosity for a galaxy

of this type. The SBH that powers the active nucleus appears to be accreting at a super-Eddington rate, $L/L_E \approx 3$, similar to the accretion rates inferred in other NLS1s. Ejection of the SBH from the ULIRG is unlikely for a number of reasons, the strongest of which is the presence of narrow emission line gas at the same redshift as the quasar nucleus; this gas could not have been retained if the SBH was ejected from the companion galaxy. We find no compelling evidence that the quasar in HE0450-2958 is either a “naked” SBH ejected from its host galaxy, or that it has an anomalously dark host galaxy.

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